Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 11, No. 3, September 2023, pp. 643~655
ISSN: 2089-3272, DOI: 10.52549/ijeei.v11i3.4530

A Review of Energy Management of Renewable Multisource in Industrial Microgrids

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Article Info

Article history:

Received Feb 18, 2023
Revised Jun 17, 2023
Accepted Jul 28, 2023

Keywords:

Distributed energy system
Energy management system
HVDC transmission
Multi-microgrids
Power electronics

ABSTRACT

This review aims to consolidate recent advancements in power control within microgrids and multi-microgrids. It specifically focuses on analyzing the comparative benefits of various architectures concerning energy sharing and demand cost management. The paper provides a comprehensive technical analysis of different architectures found in existing literature, which are designed for energy management and demand cost optimization. In summary, this review paper provides a thorough examination of power control in microgrids and multi-microgrids and compares different architectural approaches for energy management and demand cost optimization.

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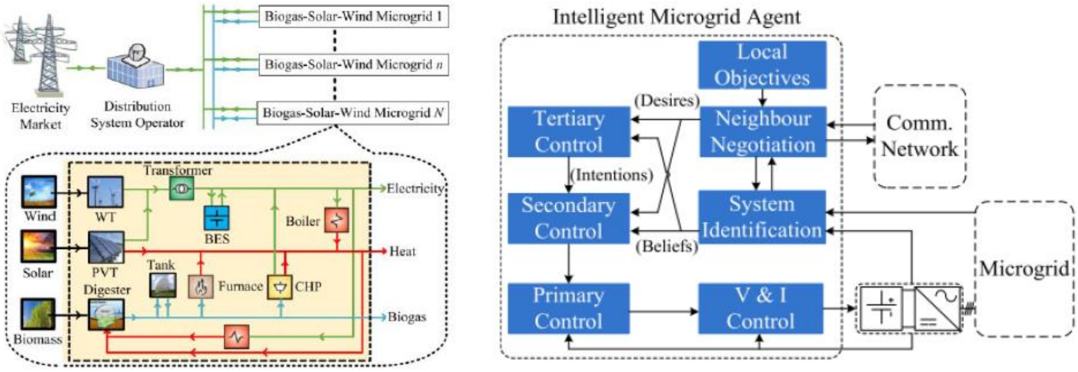
1. INTRODUCTION

According to the U.S. Department of Energy's criteria, a microgrid (MG) is a network of interconnected energy storage systems and distributed generators (DGs). It functions as a localized electricity supplier at the distribution level, capable of operating independently or in coordination with the main power grid [1,2]. A microgrid typically consists of diverse distributed generation units, including wind turbines (WT), photovoltaic (PV) systems, combined heat, and power (CHP) plants, and combined cooling, heat, and power (CHP) plants. These units can provide both electrical and thermal energy simultaneously.

Microgrid technology provides numerous technical advantages. Firstly, it greatly reduces power losses during transmission, surpassing the efficiency of conventional power systems. Secondly, microgrids offer the flexibility to operate both as independent standalone systems and as interconnected networks with the main power grid. This versatility ensures adaptability to different scenarios and grid conditions. Thirdly, effective energy management within microgrids enables the optimal utilization of stored energy reserves during periods of high demand, leading to cost savings per kilowatt hour ($/kWh) and maximizing financial gains. Lastly, in situations of emergencies or disruptions in the main grid, interconnected microgrids have the capability to isolate themselves and function autonomously, enhancing the overall reliability and resilience of the local power supply [3].

To summarize, a microgrid is a decentralized network consisting of distributed generators and energy storage systems. It functions as a localized electricity supplier, providing several benefits. These include reduced power losses, the ability to operate in different modes, cost optimization through efficient energy control, and enhanced reliability during grid outages. Microgrids offer a more efficient and flexible approach to electricity supply, ensuring reliable and sustainable power distribution at a local level.



(a) (b)

Figure 1. (a) DG expansion and interconnection of multiple MGs and (b) Multi-agent local control for distributed decision making. Extracted from [4] and [5]

With the growth of distributed generators (DGs) and the energy market liberalization, distribution networks have undergone significant changes, similar as in [4] and [5]. They have transitioned into a distributed structure that interconnects multiple microgrids (multi-MGs), as illustrated in Figure 1a. These multi-MGs consist of a combination of solar thermal collectors and photovoltaic panels, enabling simultaneous heat and electricity generation through a combined cycle methodology known as CHP (Combined Heat and Power).

Each microgrid utilizes various energy converters and storage devices to meet the energy demand in terms of quality and quantity. This new structure provides flexibility and contributes to a more competitive market, where consumers can choose energy suppliers from different locations based on price, and the generators can extend their bidding beyond their local area. However, managing energy control within this complex system becomes more intricate, requiring the integration of different control approaches, such as the use of multi-agent control depicted in Figure 1b.

2. STATE OF ART

The adoption of distributed renewable energy (RE) sources has gained significant popularity in both residential and industrial environments. Consequently, the effective management and control of energy storage systems within microgrids (MGs) have become crucial research areas.

To address these challenges and optimize energy management, various strategies have been proposed. This study investigates the control strategies for power routing that integrate hybrid systems consisting of diverse non-conventional energy sources and flexible demand within industrial facilities. The primary objective is to develop efficient control, management, and power transfer mechanisms among different types of MGs, including AC, DC, and Hybrid, while incorporating renewable energy sources.

By examining these control strategies, this research seeks to enhance the overall performance and efficiency of MGs, enabling the seamless integration of multiple energy sources and accommodating fluctuating demand. The findings of this study will contribute to the advancement of energy management practices and promote the utilization of renewable energy in industrial settings.

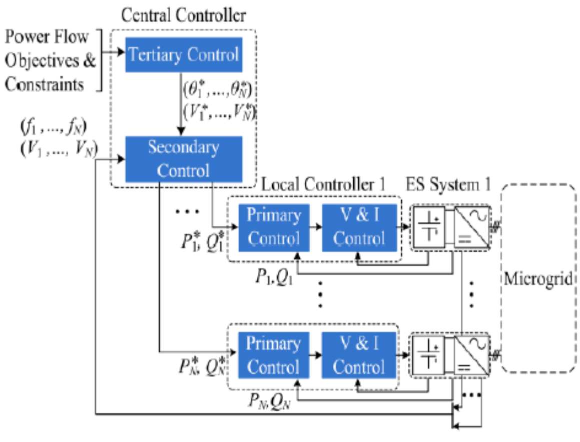


Figure 2. Classification of control types in MG. Extracted from [5].

It considers the above mentioned in [5], that exists three types of control for an MG:

1. Primary control: in charge of voltage and frequency control, reduction of conversion losses, active and reactive power of the system, and power quality control (flickers, harmonic compensation, among others), as developed in [6,7]. Please look at Figure 2. This primary control is essential for the network stability.
2. Secondary Control: in charge of compensating voltage/frequency caused by the primary control, as developed in [8,9].
3. Tertiary Control: Control manages the optimal control of energy flow from distributed renewable energy sources between isolated and non-isolated MG.

Developing a multi-objective optimal control algorithm at the tertiary level is required to achieve optimal control of energy flow within the microgrid (MG). This algorithm is essential in the MG operation, making necessary corrections to meet the demand profiles.

Tertiary control holds particular significance as it determines the activation of storage systems to effectively smooth out demand peaks. It operates at a higher level compared to the primary and secondary control loops, which are responsible for maintaining stability in the distributed generators (DGs). The primary and secondary control loops regulate the fundamental technical parameters of the DGs to ensure their stable operation.

To better understand the interplay between these control loops, please refer to Figure 3, which provides a visual representation of their relationships and functions. By implementing this comprehensive control framework, the MG can optimize its energy management, enhance stability, and effectively respond to dynamic changes in demand and supply.

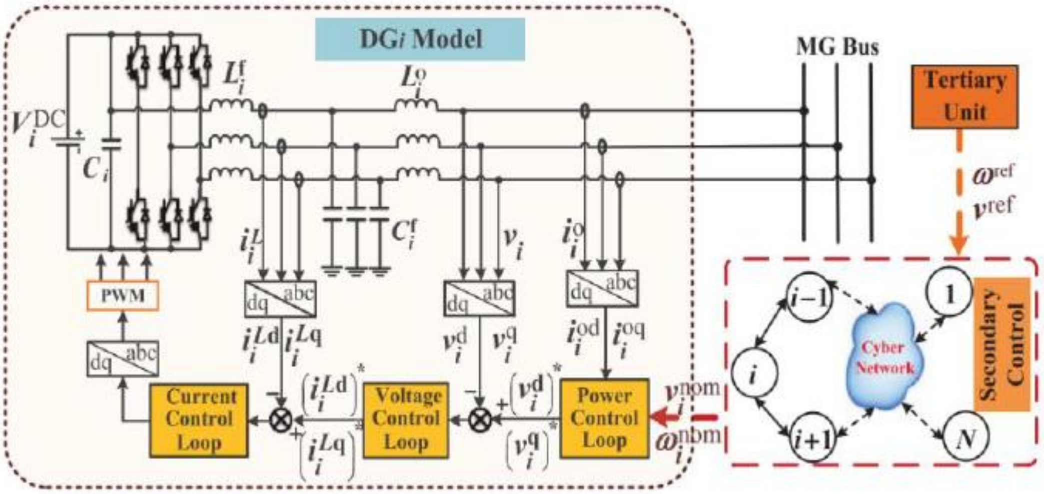
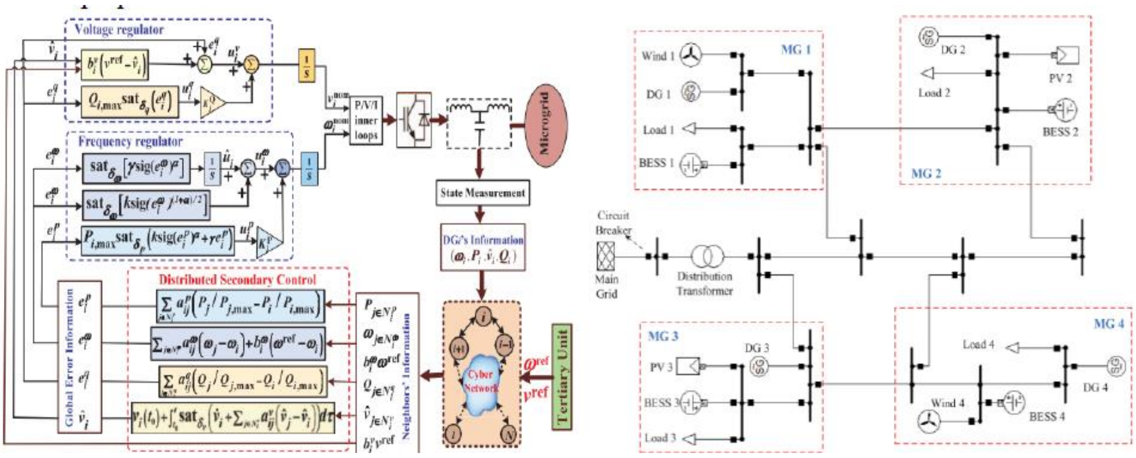


Figure 3. The DG stability is guaranteed by all types of control in MG. Extracted from [10].

This research focuses on industrial microgrids (MG) that utilizes renewable energy sources such as solar energy, wind energy, biogas generated from biomass or chemical processes, combined cycle CHP, or other clean sources. Additionally, determining the most feasible energy storage method(s) based on the specific conditions that considers the implementation costs as crucial. The objective of establishing optimal control mechanisms that enable the transition towards a Zero industry, where energy consumption is entirely sourced from renewable sources, or a prosumer industry that consumes renewable energy while exporting surplus energy for economic gain.

Different multi-MG control levels are proposed in [10]. These controls manage the relevant electric parameters to guarantee high power quality. For [11], the energy balance of the whole network must be adjusted, meaning that the power generated by renewable sources is redirected to where extra power is required In [12], the control of multiple interconnected MGs was proposed, see Figure 4a, with a multi-agent system and distributed EMS to achieve plug-and-play and peer-to-peer capabilities. Figure 1b and Figure 4b. Subsequently, various distributed power management methods under this architecture have been proposed. For example, in [13], a distributed algorithm based on an alternating direction multiplier method (ADMM) was proposed to achieve optimal power flow by partitioning a power grid into multiple regions.



(a) (b)

Figure 4. (a) Multi-MG control levels proposed by [10], (b) Connection topology for Multi-MG energy control [11].

In [14], a single-period energy trading algorithm was proposed based on dual decomposition for multiple MG systems. Finally, in [15], the optimal scheduling problem for multiple MG interconnection systems was investigated by proposing a Nash bargaining utility sharing.

2.1. Evaluation of energy management and control techniques in microgrids documented in the literature.

When evaluating energy management and control techniques, the authors of [16-18] consider the uncertainties associated with the demand in multi-MG systems. To address this, an Energy Management System (EMS) is established in [16], which considers the daily demand. Additionally, [17] and [18] propose a daily dispatch strategy. However, these previous works are limited to semi-distributed MGs, which rely on a single centralized unit for EMS operations. Another limitation lies in the difficulty of predicting market uncertainties in advance. Robust optimization emerges as a solution for optimizing the objective function without considering uncertainties. This approach has been utilized in various energy systems, including energy demand response [19], energy sales [20], integration of electric vehicles (EVs) into MGs [21], and ancillary services [22].

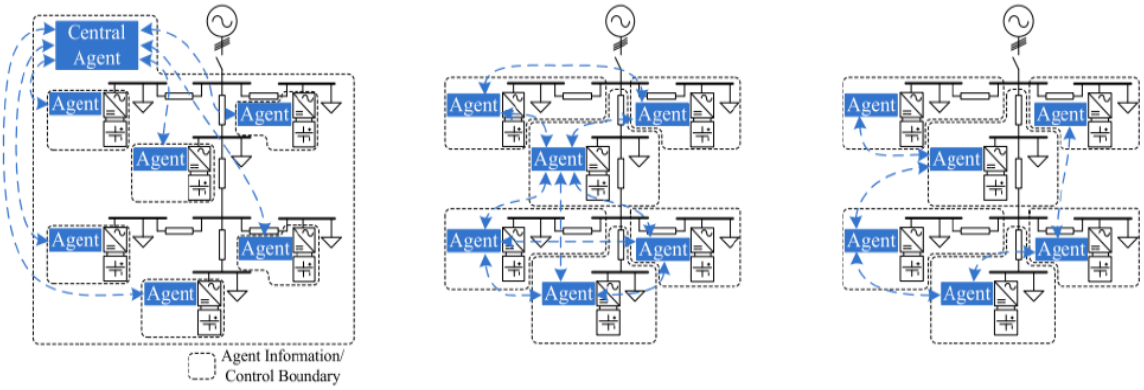
The problem with semi-distributed systems is the centralization of control decision-making based on gathered information. Some MG operators may hesitate to share information, which is crucial for predicting demand behavior and associated MG dynamics. Communication issues and erroneous information can impede the MG's operation and even lead to instability. On the other hand, the predictive control model (PCM) has been implemented in studies [23], [24] for optimal power flow control. [25] introduces a multi-objective optimization approach with high DG penetration using renewable energies. Various stochastic strategies for optimal energy management are discussed in [26, 27].

A commonly used stochastic formulation is the two-stage problem. Reference [28] suggests a stochastic formulation for minimizing operating costs, including grid energy losses of an MG. Similar two-stage formulations are presented in [29-31].

A limitation of this formulation is the assumption that all uncertainty is revealed at once. For a multistage formulation, the uncertainty is revealed in different stages, and the system control is gradually updated as the uncertainty is revealed. This formulation is widely used in hydropower scheduling [32], and stochastic dual dynamic programming is an efficient technique for solving large-scale multistage stochastic problems [33].

Several SDDP-based MG creates storage management methods, which are proposed in the literature. [34] suggests an MG model that minimizes procurement costs under uncertain wind generation, balancing load through micro-generators and load shifting. Reference [35] has a similar formulation, including power loss minimization and uncertain prices. In [36], the cost is minimized for a private household with battery storage and uncertain PV generation. [37] balances uncertain wind generation with conventional generation and battery storage, incorporating a cost associated with battery level variation.

Isolated/non-isolated MGs are analyzed in [38], while industrial MGs are investigated in [39]. A hierarchical power scheduling approach is proposed in [40], and the authors in [41] present a heuristic-based methodology for daily unit commitment. An optimal operational strategy based on quadratic programming and particle swarm optimization is described in [42]. [43] and [44] perform real-time control using a two-stage approach. Finally, [45] develops an adaptive partitioned contextual learning algorithm for operational cost minimization of an MG with high renewable energy penetration.



(a) Hierarchical (b) Topology Based Message Passing (c) Fully Distributed

Figure 5. Control of multiple DGs in a MG by agents. Extracted from [5].

The energy control of multiple DGs can be implemented based on agents, as shown in Figure 5. This methodology allows each local agent to have a DG at its command, instantly making decisions. This agent establishes communication with the central agent to report its status and receives orders that will only be changed in new communication. If no communication is established, the agent will follow previous instructions and monitor the network stability to decide whether to isolate the DG.

2.2. Study of technical requirements of case study considering alternative energy generating sources.

To develop the case study, introducing Distributed Generation (DG) with a high component of renewable energies is necessary. New DG requires assessing the availability of resources such as biogas, solar radiation, and wind regime, considering the local conditions of the industry. The concept of an energy hub or energy router is utilized, where industrial Microgrids (MGs) are connected to the distribution system. These MGs can supply excess energy to other MGs through the distribution system or draw power from it to meet local demand when the energy from the Energy Storage System (ESS) is insufficient. The research focuses on determining the industrial storage system(s) needed for self-supply without relying on the grid. Various multi-energy methods have been developed to achieve this goal, such as gas flaring for electricity generation and waste heat utilization in cogeneration and trigeneration.

The increasing demand for affordable and diverse energy services has led to the growing significance of biogas in microgrids (MGs) [47], [48]. Researchers have explored the optimal scheduling of hybrid Renewable Energy (RE) sources, including biogas, solar, and wind, to establish complementary energy supplies for electricity, heating, and gas [49]. This scheduling involves coordinating the multi-energy schedules of individual MGs and enabling energy exchange between them. However, the high-bandwidth network required to handle system information and increased data traffic within the optimization scheme can pose challenges, especially in tracking and sharing information among MGs [50]. Consequently, achieving multiple network scheduling becomes a complex optimization problem due to uncertainties in RE, multiple energy couplings, high-dimensional variables, multiple energy demands, and limited bandwidth.

Extensive studies have been conducted on the coordinated operation of multiple MG systems, focusing on active energy exchange through the electricity market and interconnected microgrids. Previous works have proposed distributed convex optimization frameworks for economic dispatch in isolated MGs and energy exchange between MGs to ensure supply-demand balance [50], [51]. Online energy management systems have also been proposed [52-54], utilizing distributed algorithms to optimize internal energy devices and external energy trading with the electricity market and other MGs. Game theory has been employed [15], [55], [56] to introduce incentive mechanisms for transactive energy trading and fair benefit sharing. However, these studies have primarily focused on systems with a single energy carrier.

While investigations have been carried out on CHP-based MGs at the distribution grid level [57], [58], there is still a need to explore the coordination of multi-energy systems and interactive energy exchange among multiple MGs. Robust energy management systems have been designed to account for uncertainties associated with renewable sources, time-varying loads, and energy prices. Still, they have mainly focused on improving system availability through electricity exchange, neglecting the role of gas exchange and multi-energy couplings in enhancing system operational availability.

In terms of multi-MG scheduling approaches, there are two types: centralized and distributed. The centralized approach, as mentioned earlier, faces challenges. On the other hand, the distributed approach relies on algorithms such as the ADMM method [13], [51], Lagrangian relaxation [50], predictive control model [53], [54], and consensus algorithms [59], [60] to solve the multigrid scheduling problem.

Regarding Energy Storage Systems (ESS), various technologies can be classified as follows [61]:

2.2.1. Mechanical Storage Systems (MSS): Mechanical energy storage systems (MES) are advantageous as they can efficiently convert and store energy from different sources [62]. Currently, three techniques are widely used: Flywheel, pumped-hydraulic storage, and Compressed-Air Energy Storage Systems (CAES). Flywheel technology stores energy in kinetic form, while pumped-hydraulic storage stores energy in potential form by using an electric machine to store a fluid, such as water, at high altitudes for controlled use as a generator. CAES stores pressure energy by compressing gas, typically air, in a reservoir or cavern [63]. Please refer to Figure 6 for a visual representation. During periods of low energy demand, excess energy drives a reversible motor or generator unit, which runs a chain of compressors to inject air into the storage unit.

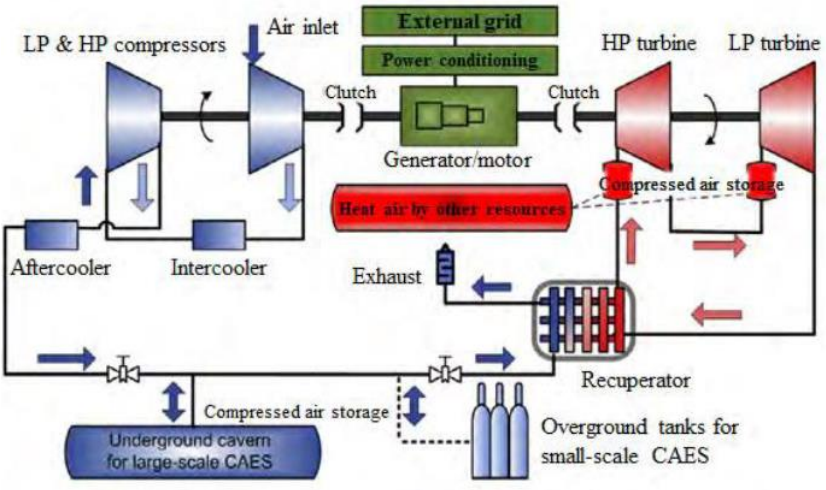


Figure 6. Simplified diagram of CAES. Extracted from [61]

***2.2.2. Chemical Storage Systems* (CSS):** This system stores a significant amount of energy over an extended time. In the CSS system, energy is stored in the chemical bonds of atoms and molecules, which can be released by electron transfer reactions to produce electricity directly. Examples of this technology are Pb, Li-ion, Li-Air, and other types of batteries, as well as so-called Fuel Cells. The latter costs approximately $525/kW.

2.2.3. Electrochemical Storage Systems (EcSS): Ultracapacitors, Super Magnetic Energy Storage Systems (SMEs) Energy is stored in the magnetic field by circulating current in a superconducting coil with the help of an AC to DC converter (charging mode). However, the DC-to-AC converter (discharge mode) can return the stored energy to the grid. Therefore, their power range for commercial use is from 0.1 to 10 MW, and their installation cost is high ($10,000/kWh) [64] [65].

2.2.4. Electrical Energy Storage Systems (EESS): Energy can be stored by modifying electric or magnetic fields with the help of capacitors or superconducting magnets [66]. The current power grid system faces the challenge of integrating the transmission and distribution system with renewable energy sources.

2.2.5. Thermal Storage Systems (TSS): TSS can store energy in heat, releasing energy when required. This technology is suitable for use in the industrial sector, such as heating or cooling systems, load shifting, and power generation.

***2.2.6. Hybrid Storage Systems* (CSS):** This technology combines the advantages of different storage systems to improve their technical performance. The literature review on Hybrid Energy Storage System (HESS) technology shows that for MG applications, the integration of battery/SC, battery/SMEs, battery/FC, FC/SC, and SC/RFB is possible [67-72]. The combination of Battery/SC technologies is now very popular and widely applicable in the industrial sector.

2.3. Technical-economic evaluation of energy generation and control systems.

To develop the technical-economic evaluation, we need to define indicators that determine the cost of maintenance, generation, storage, and transportation of the energy units to optimize the energy dispatch. In this case, technical-economic evaluation indicators of the energy generation systems are proposed, such as (See Table 1):

Table 1. Technical-economic evaluation indicators

Technical evaluation	*Economic evaluation*
1. kWh needed to supply estimated demand. 2. Cost of demand flattening and power factor correction techniques. 3. Need new devices, such as SSTs, UCaps, or others, for grid isolation and fault testing to ensure MG stability. 4. Hours of stored energy usage vs. energy demand. 5. Availability of non-projected demand response. 6. Overall energy efficiency of the MG. 7. Local efficiency of power converters involved for main bus link. 8. Control of basic network parameters and QoP.	1. Present value of the RES kWh. 2. Generation unit maintenance cost. 3. DER implementation cost vs. depreciation time. 4. Plant factor of the technology used. 5. Generation factor according to time of day under standard characteristic profile. 6. Reliability of the MG. 7. Energy requirements profile/hour. 8. Energy unit losses in transmission. 9. kWh value in the electricity market. 10. Cost of storing excess energy units generated.

2.4. Analysis of architectures for energy and demand cost management.

Ensuring stability in microgrids (MGs) despite renewable energy sources' variability and intermittent nature is a significant challenge. A tertiary-level energy control system plays a vital role in achieving this stability. The primary-level control monitors and regulates voltage, current, and frequency within the microgrid. In contrast, the secondary-level control manages the active and reactive power of the energy transfer bus. It is important to apply these control measures simultaneously to each renewable energy source within the MG. Figure 7 illustrates specific converters, such as rectifiers and choppers, tailored to each energy source.

Due to the inherent variability of renewable sources, there may be instances when excess energy is generated. This surplus energy can be fed back to the grid through Net Metering or stored in an Energy Storage System (ESS). However, utilizing multiple energy conversions can reduce overall energy efficiency. Therefore, exploring alternatives that minimize the number of converters is essential.

Furthermore, the control system needs to determine whether the MG should operate in an interconnected mode with the grid or in an isolated mode. Opting for grid interconnection can reduce the implementation costs of the ESS, as any excess energy produced can be readily supplied to the grid.

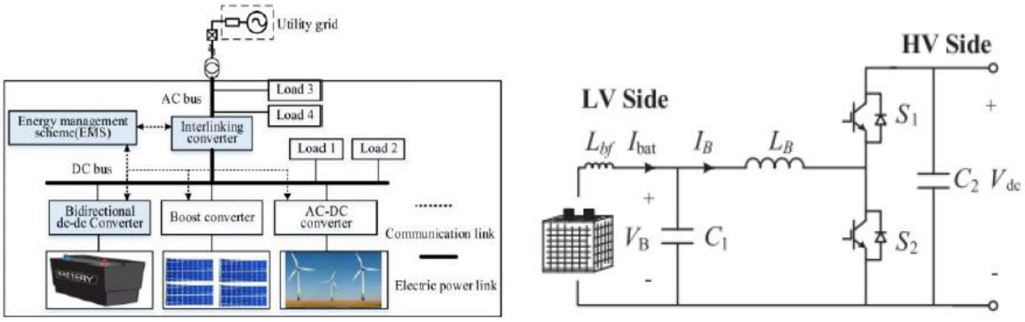


Figure 7. Multiple energy sources and converters + ESS. Extracted from [73].

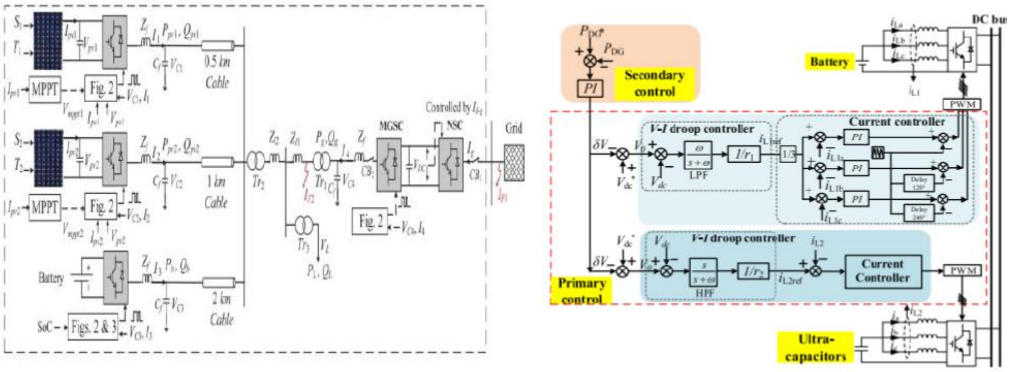


Figure 8. Considerations in industrial application. Extracted from [74].

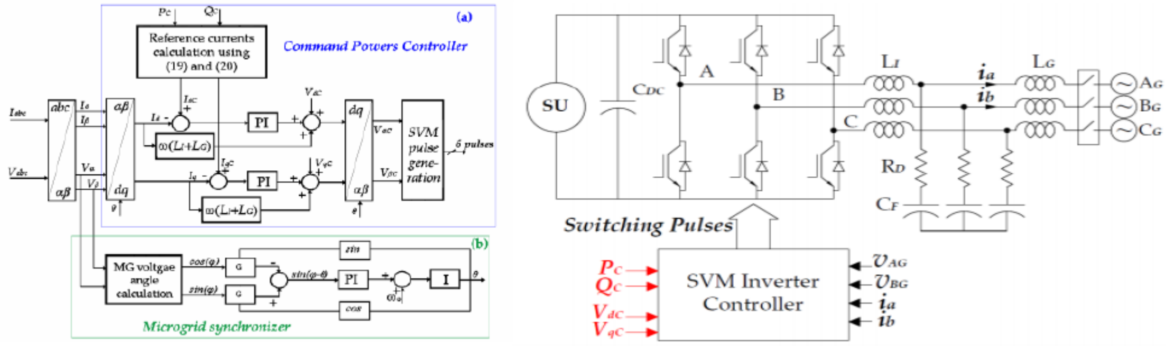


Figure 9. Second level control for control and injection of current to the network.

Some dc-dc converters (buck-boost type) are implemented in [73] to manage the energy flux between the high and low-voltage side to perform the link. On the other hand, the development of energy control algorithms for microgrids (MGs) in [74] is highly dependent on the specific application and the number of energy sources involved, as depicted in Figure 8. At the first level of control, the voltage and current are monitored to ensure that the energy source meets the minimum technical requirements for injecting current into the DC bus. Each Maximum Power Point Tracking (MPPT) associated with the photovoltaic (PV) arrays aims to maximize power transfer by utilizing techniques like Perturb and Observe. Figure 9 illustrates the secondary control (P & Q) performed by an inverter to regulate reactive power and deliver the desired active power. This control mechanism utilizes Clarke-Park transforms to simplify three-phase systems into two-phase systems.

Figure 10 presents a flow diagram outlining the energy control of an MG based on the research conducted in [75]. This approach leverages sensor data to determine the MG's connection type (isolated or non-isolated) and whether synchronization with the grid is necessary. In the case of grid interconnection, the MG must fulfill two crucial tasks: (a) synchronize with the grid phases using a Phase-Locked Loop (PLL) and (b) monitor $/kWh values to determine if power should be imported from or exported to the grid. Importing power enables the MG to meet local demands that available resources cannot fulfill or to store energy in the Energy Storage System (ESS). Conversely, during surplus conditions, the optimal price per kWh must be determined for injecting power into the grid, thereby maximizing economic profit.

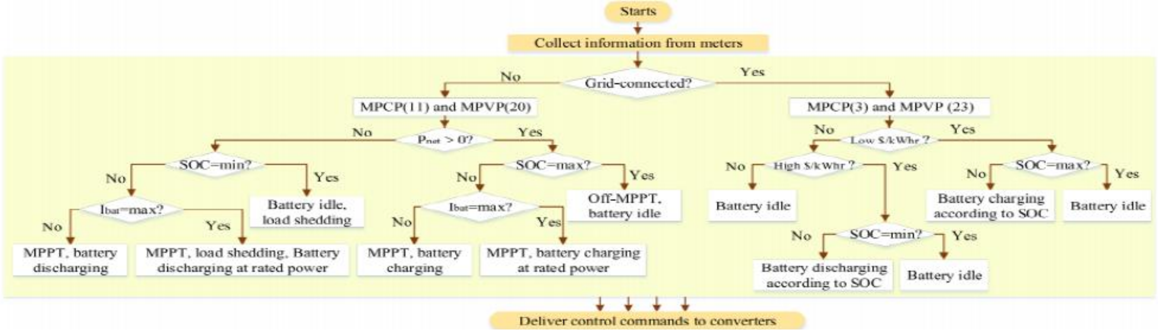


Figure 10. MG energy control flowchart. Extracted from [75]

When analyzing microgrids (MGs) with DC bus interconnection, it is crucial to consider the nature of renewable energy generation, which often produces continuous signals. In this context, employing a DC bus for power transmission within MGs becomes feasible if the connected loads operate on DC. Similar as in [76]. To explore the control strategies for power management and network stability, Figure 11 provides an overview of the strategies previously studied in the literature.

These strategies can be broadly categorized into non-hierarchical control and hierarchical control. Non-hierarchical control involves primary control of individual power generation systems and Energy Storage Systems (ESS). This control ensures that the DC bus maintains a consistent average DC value and facilitates maximum power flow. Suppose the decentralized control system (as shown in Figure 12) or the distributed control system detects unstable or unfavorable conditions in the bus. In that case, the system can disconnect from the main bus until normal operating conditions are restored.

However, it's important to note that centralized control, which falls under non-hierarchical control, is not recommended for large MGs or the interconnection of multiple MGs due to its limited redundancy and interdependence. Hence, hierarchical control methods should be explored for improved reliability and scalability in such cases.

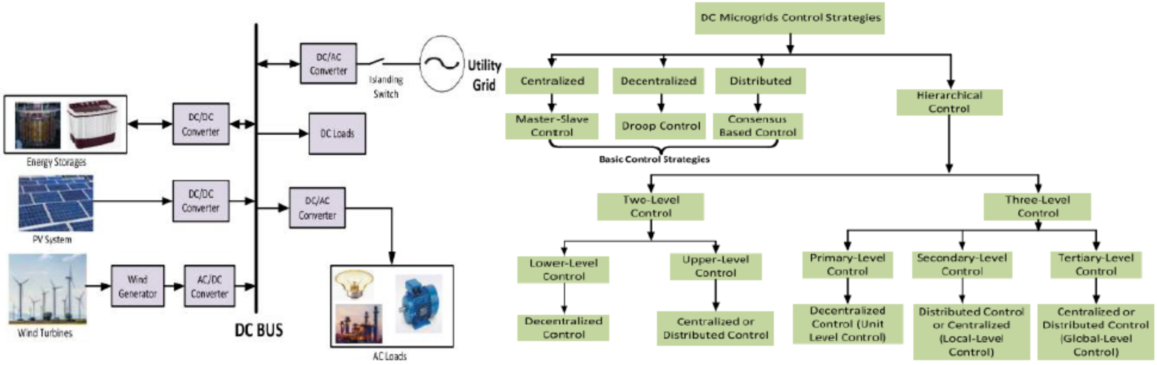


Figure 11. MG Control Strategies with DC bus. Extracted from [76].

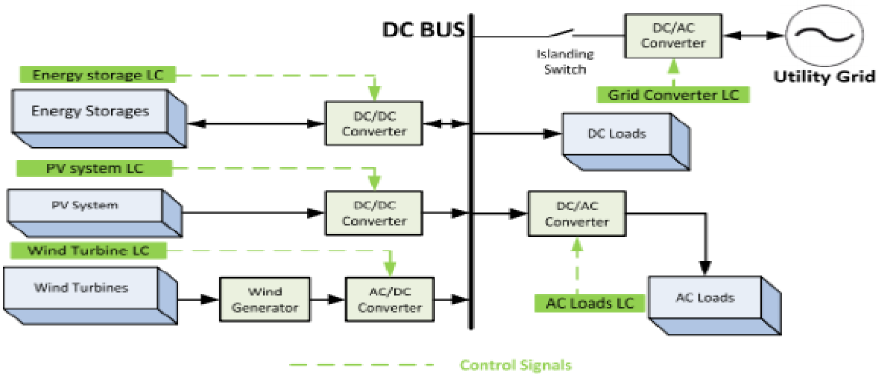


Figure 12. Decentralized control in MG structure with DC bus. Extracted from [76].

Decentralized control offers greater flexibility in the operation and energy management of the DC bus. Each system has full autonomy to establish its operating conditions while ensuring the voltage stability of the DC bus. This decentralized control approach enables scheduled maintenance of individual MG generation systems without disrupting the overall system operation.

In contrast for [77], the centralized systems rely heavily on their communication systems, as shown in Figure 13. With accurate information about the status of each component within the MG system, the central controller may make correct decisions that could lead to system instability. In this research, it is crucial to emphasize that high-level control, such as energy and power flow control, should be carried out centrally. Knowledge of each system's energy supply and demand status makes it possible to redirect the energy flow effectively. On the other hand, the first and second-level controls can be implemented locally and in a decentralized manner.

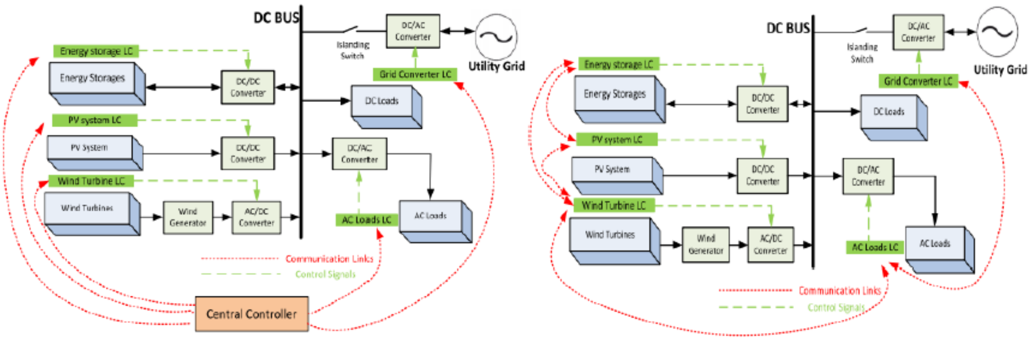


Figure 13. Centralized and distributed control for an MG with DC bus. Extracted from [77].

3. CONCLUSION

Different topologies were analyzed and studied, especially the power bridge, which is adequate for voltage scalability (HVDC) that permits transmitting energy packets with high efficiency. This HVDC transmission will reduce the total current between grids, improving the power losses. This power loss occurs over the wires, especially when the energy is transmitted in AC mode. On the contrary, when the DC mode is used, the skin effect, eddy currents, and other effects associated with the AC mode disappear.

Conversely, industrial multi-microgrids can integrate different energy-renewable sources inside their clusters without affecting their stability and controllability. All computational tests determine the technical viability of incorporating renewable sources and ESS. Different methods for transferring between grids or energy multi-sources and ESS were analyzed for this case. It is important to highlight that a problem with any source can be isolated without affecting the functionality of the power bridge. Finally, using the proposed energy management method applies primary, secondary, and tertiary control, which guarantees the stability of the industrial microgrid.

ACKNOWLEDGEMENTS

Authors, thank the sponsor and financial support to Minciencias Postdoc scholarship state 848-2019.

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